

Postprint: Design of Automatic Temperature Compensation Mechanism for Beam Expander Optical System

Authors: Li Haibo

Date: 2022-12-05T00:00:00+00:00

Abstract

Beam expansion optical systems exhibit high sensitivity to temperature. To mitigate temperature effects on the optical system, an automatic temperature compensation mechanism was designed. This mechanism achieves mutual compensation through differential thermal expansion coefficients between materials, thereby ensuring mirror spacing stability. Variations in primary-secondary mirror spacing were analyzed using ANSYS software for temperature increases from 20°C to 30°C, 40°C, and 50°C, followed by optical simulation of the modified system using ZMAX software. Analysis results indicate that without the automatic temperature compensation mechanism, primary-secondary mirror spacing changes by 0.02722 mm, 0.05443 mm, and 0.08164 mm, respectively, and system wavefront error Root Mean Square (RMS) degrades from 0.0013λ to 1.3898λ , 2.7782λ , and 4.1656λ ($\lambda = 632.8$ nm), failing to meet optical imaging quality requirements. With the automatic temperature compensation structure, spacing changes are reduced to 0.00005 mm, 0.00009 mm, and 0.00014 mm, respectively, and wavefront error RMS increases from 0.0013λ to only 0.0026λ , 0.0046λ , and 0.0072λ , still satisfying optical imaging quality requirements. Therefore, this automatic temperature compensation mechanism can effectively suppress the influence of large temperature differences on beam expansion optical system imaging quality.

Full Text

Design of Automatic Temperature Compensation Mechanism for Beam Expanding Optical System

Li Haibo

CAS Nanjing Astronomical Instruments Co., Ltd., Nanjing 210042, China
Email: hbli@nairc.ac.cn

Abstract

Beam expanding optical systems exhibit high sensitivity to temperature variations. To mitigate thermal effects on optical performance, this paper presents an automatic temperature compensation mechanism that leverages differential thermal expansion coefficients among materials to maintain stable mirror spacing. Finite element analysis using ANSYS was performed to evaluate primary-secondary mirror separation changes as the system temperature increased from 20°C to 30°C, 40°C, and 50°C. Subsequent optical simulation analysis of the thermally perturbed system was conducted using ZMAX software. The results demonstrate that without automatic temperature compensation, the primary-secondary mirror spacing changed by 0.02722 mm, 0.05443 mm, and 0.08164 mm, respectively, causing the system wavefront error RMS to degrade from 0.0013λ to 1.3898λ , 2.7782λ , and 4.1656λ ($\lambda = 632.8$ nm), which fails to meet optical imaging quality requirements. With the proposed compensation mechanism, the mirror spacing variations were reduced to 0.00005 mm, 0.00009 mm, and 0.00014 mm, respectively, and the RMS wavefront error increased only marginally from 0.0013λ to 0.0026λ , 0.0046λ , and 0.0072λ , remaining well within imaging quality specifications. Therefore, the automatic temperature compensation mechanism effectively suppresses the impact of large temperature differentials on the imaging quality of beam expanding optical systems.

Keywords: beam expanding optical system; automatic temperature compensation mechanism; mirror spacing; ANSYS; ZMAX; system wavefront error

Funding: National Natural Science Foundation of China (12141304)

Received: 2022-09-20; **Revised:** 2022-10-10

Introduction

Beam expanding optical systems serve as critical components in laser communication and laser ranging applications, playing vital roles in astronomical observation, satellite communications, global positioning systems, and national defense infrastructure. To meet the operational requirements of laser ranging systems, reference [2] designed a 2-6 \times transmissive continuous zoom system, while reference [3] developed an off-axis three-mirror system achieving optical zoom through adjustment of the secondary and tertiary mirrors, with all reflective surfaces employing aspherical optics. As the deployment of beam expanding systems expands, so do the demands for operational stability. However, large temperature differentials significantly impact system stability because thermal expansion and contraction are inherent properties of most materials. In environments with substantial temperature variations, non-uniform thermal stresses within components generate complex thermal strains, leading to thermal misalignment of optical elements and degraded optical performance [4]. Positional deviations of optical elements caused by support structure deformation [5] have

long challenged researchers and engineering designers. Consequently, increasing attention is being focused on improving temperature stability through structural design innovations. In 2016, reference [6] implemented a motor control system for temperature compensation, which effectively regulated the system temperature range but struggled to ensure temperature uniformity, thereby compromising imaging quality. In 2021, reference [7] designed a temperature compensation mechanism for a low-temperature off-axis reflective collimation system that significantly improved thermal stability; however, this approach relied solely on the low expansion coefficient of Invar without incorporating a reverse temperature compensation mechanism, resulting in still-substantial imaging quality degradation.

During the development of a 200 mm aperture laser transmitting beam expander, researchers observed that large temperature variations severely impacted system image quality, preventing the system from meeting wavefront error requirements and consequently degrading communication performance. To address this issue, this paper proposes an automatic temperature compensation mechanism featuring a reverse temperature compensation device. By exploiting differences in thermal expansion coefficients and directional expansion characteristics among various materials, and through theoretical calculations of appropriate mechanical structure dimensions, the total variation in mirror spacing can be made to approach zero across a 30°C temperature range, thereby suppressing temperature-induced effects on system image quality. Within a +30°C temperature variation range, ANSYS software was used to analyze the effect of the automatic compensation mechanism on primary-secondary mirror positioning, followed by ZMAX optical simulation analysis of the thermally perturbed mirrors. The results confirm that the mechanism effectively reduces temperature-induced mirror spacing variations and successfully mitigates thermal effects on beam expanding optical system imaging quality.

1. Mechanism of Automatic Temperature Compensation for Beam Expanding Systems

The beam expanding optical system specifications are: 200 mm aperture, 16× expansion ratio, and on-axis wavefront $\text{RMS} \leq \lambda/20$ @ 632.8 nm after alignment. The system employs a coaxial design without a real focal point; a 12.5 mm diameter laser beam enters the secondary mirror and, after reflection from both secondary and primary mirrors, emerges as a 200 mm diameter beam for transmission, enabling laser transmission and reception when paired with a receiving telescope.

[Figure 1: see original paper]

Fig. 1 16× beam expansion system diagram

Table 1 Mirror parameters

The relative positioning among the primary mirror, secondary mirror, and window optics significantly affects imaging quality. To mount these components while maintaining their positional relationships, the beam expander structural design is configured as shown in Figure 2. The system comprises the lens tube assembly, window optics assembly, secondary mirror assembly, primary mirror assembly, rear housing assembly, and automatic temperature compensation mechanism. The lens tube, fabricated from Q235 steel through welding, serves as the main structural support for mounting other assemblies. The window optics are installed in the window assembly, which connects to the lens tube. The primary mirror is mounted in a primary mirror cell featuring a side support mechanism that contacts the mirror through polytetrafluoroethylene (PTFE) structures. By exploiting the different thermal expansion coefficients among the steel mirror cell, the microcrystalline glass primary mirror, and the PTFE side support, automatic temperature compensation is achieved, reducing thermally induced mechanical stress on the primary mirror. The secondary mirror is bonded to an Invar sub-cell and installed in the secondary mirror assembly, which connects to the temperature compensation mechanism and is isolated from the lens tube. A five-dimensional adjustment mechanism at the secondary mirror position ensures proper optical alignment of the primary-secondary mirror system.

[Figure 2: see original paper]

Fig. 2 Structure diagram of beam expanding system lens tube

[Figure 3: see original paper]

Fig. 3 Schematic diagram of temperature compensation mechanism for beam expansion system

Given the substantial thermal sensitivity of the beam expanding optical system, an Invar (grade 4J32) connecting mechanism is employed between the primary and secondary mirrors, with an aluminum reverse temperature compensation mechanism at the secondary mirror position, as illustrated in Figure 3. The key structural components for temperature compensation include: Invar rod component 1, secondary mirror steel structure 2, reverse compensation aluminum component 3, Invar spacer component 4, and Invar secondary mirror cell component 5. Invar rod component 1, made from low-expansion Invar material, primarily minimizes temperature-induced mirror spacing variations. Secondary mirror steel structure 2 mounts the secondary mirror and reverse compensation aluminum component 3. Reverse compensation aluminum component 3, fabricated from high thermal expansion coefficient aluminum, provides reverse temperature compensation. Invar spacer component 4 reduces forward expansion, while Invar secondary mirror cell component 5, also made from low-expansion Invar material, mounts the secondary mirror and minimizes thermal effects. Component materials and properties are listed in Table 2. With plane 6 established as the thermal reference surface, temperature increases cause Invar rod component 1, secondary mirror steel structure 2, and Invar spacer component 4 to expand in the $+z$ direction, while reverse compensation aluminum compo-

ment 3 and Invar secondary mirror cell component 5 expand in the $-z$ direction. By designing appropriate component lengths based on the different thermal expansion coefficients and directional expansion characteristics, theoretical calculations yield a total variation approaching zero, thereby achieving automatic temperature compensation. This structure effectively suppresses temperature-induced primary-secondary mirror spacing variations, ensuring optical system imaging quality.

The thermal expansion formula for metallic materials is:

$$\Delta L = \alpha L(T_2 - T_1) \quad (1)$$

where ΔL is the axial elongation (mm), α is the linear thermal expansion coefficient, L is the material length (mm), T_1 is the initial temperature ($^{\circ}\text{C}$), and T_2 is the operating temperature ($^{\circ}\text{C}$).

The mirror spacing change ΔZ is given by:

$$\Delta Z = \alpha_1 L_1(T_2 - T_1) + \alpha_2 L_2(T_2 - T_1) + \alpha_4 L_4(T_2 - T_1) - \alpha_3 L_3(T_2 - T_1) - \alpha_5 L_5(T_2 - T_1) \quad (2)$$

where α_1 is the Invar linear expansion coefficient; α_2 is the steel linear expansion coefficient; α_3 is the steel linear expansion coefficient; L_1 is the length of Invar rod component 1; L_2 is the length of secondary mirror steel structure 2; L_3 is the length of reverse compensation aluminum component 3; L_4 is the length of Invar spacer component 4; and L_5 is the length of Invar secondary mirror cell component 5.

2.1 System Parameter Configuration

The thermal expansion coefficients and lengths of each component are listed in Table 2.

Table 2 Structural component parameters

2.2 System Temperature Analysis Results

Using 20°C as the reference temperature, ANSYS finite element analysis software was employed to analyze the relative position changes between primary and secondary mirrors at 30°C , 40°C , and 50°C . The optical axis was defined as the z -direction, with the coordinate system reference shown in Figure 4. Relative mirror positions were determined by calculating primary-secondary mirror offset through least-squares fitting of mirror vertex coordinates. Since the automatic temperature compensation mechanism is axisymmetric, temperature-induced

position changes in the x- and y-directions are negligible and were therefore ignored in the analysis. The study focused on relative vertex offset along the z-axis, with these positional changes subsequently imported into ZMAX for optical simulation to calculate wavefront error of the laser beam expander under each temperature condition.

[Figure 4: see original paper]

Fig. 4 Reference map of mirror tube coordinate system

When the temperature increased to 30°C, 40°C, and 50°C, the primary-secondary mirror position changes were analyzed for both configurations: without and with the automatic temperature compensation mechanism, as shown in Figures 5 and 6, respectively.

[Figure 5: see original paper]

Fig. 5 No automatic temperature compensation mechanism is designed

[Figure 6: see original paper]

Fig. 6 Design of automatic temperature compensation mechanism

[Figure 7: see original paper]

Fig. 7 Comparison diagram of mirror spacing change

The analysis reveals that at temperatures of 30°C, 40°C, and 50°C, the primary-secondary mirror spacing changed by 0.02722 mm, 0.05443 mm, and 0.08164 mm, respectively, without compensation, but only by 0.00005 mm, 0.00009 mm, and 0.00014 mm with the automatic temperature compensation mechanism. As clearly shown in Figure 7, the mirror spacing variation with compensation is substantially smaller than without compensation, demonstrating that the mechanism effectively suppresses primary-secondary mirror spacing changes.

2.3 System Optical Quality Analysis Results

The theoretical design performance of the beam expanding optical system at 20°C is shown in Figure 8. Optical quality analysis of the primary-secondary mirror system at elevated temperatures (30°C, 40°C, and 50°C) was performed using ZMAX optical simulation software for both uncompensated and compensated configurations, with results presented in Figures 9 and 10.

[Figure 8: see original paper]

Fig. 8 Wavefront diagram of 20°C system

[Figure 9: see original paper]

Fig. 9 System wavefront diagram (no compensation is designed)

[Figure 10: see original paper]

Fig. 10 System wavefront diagram (design compensation)

[Figure 11: see original paper]

Fig. 11 RMS comparison diagram of system wavefront error

Comparative wavefront analysis shows that when system temperature increases from 20°C to 30°C, 40°C, and 50°C without temperature compensation, the on-axis wavefront RMS values are 1.3898λ , 2.7782λ , and 4.1656λ , respectively. This large wavefront variation degrades output beam collimation and fails to meet the system requirement of $\text{RMS} \leq \lambda/20$. With temperature compensation, the on-axis wavefront RMS values are 0.0026λ , 0.0046λ , and 0.0072λ , respectively—differing from the 20°C performance by only 0.0059λ at maximum, thus satisfying the wavefront RMS specification and enabling high-quality beam transmission.

When the beam expander temperature increases from 20°C to 30°C, 40°C, and 50°C, the uncompensated system exhibits primary-secondary mirror spacing changes of 0.02722 mm, 0.05443 mm, and 0.08164 mm, with RMS wavefront error degrading from 0.0013λ to 1.3898λ , 2.7782λ , and 4.1656λ ($\lambda = 632.8$ nm), failing to meet optical imaging quality requirements. With the automatic temperature compensation mechanism, mirror spacing changes are reduced to 0.00005 mm, 0.00009 mm, and 0.00014 mm, and RMS wavefront error increases only to 0.0026λ , 0.0046λ , and 0.0072λ , respectively—still satisfying optical imaging quality requirements. Therefore, the automatic temperature compensation mechanism effectively suppresses the impact of large temperature differentials on beam expanding optical system imaging quality, providing a valuable reference for future temperature compensation designs.

References

- [1] KIM Y S, KIM H S, PARK Y C, et al. Laser beam director system monitoring the alignment state with a null reflector [C] // Proceedings of SPIE. 2007.
- [2] SHAN J, ZHANG P, FU Y H. Design of optical zooming system used for collimating laser beams[J]. Optics & Optoelectronic Technology, 2013, 11(4):72-76.
- [3] SUN X Y, ZHANG G Y, DUAN J. Investigation of controllable axial conformity for opto-mechanical structure[J]. Chinese Journal of Lasers, 2012, 39(1):229-234.
- [4] CHANG J, WANG Y, ZHANG T, et al. All reflective zoom systems for infrared optics [C] // Proceedings of SPIE. 2006.
- [5] SHAN B Z, CHEN E T, LU E, et al. Thermal/structural/optical integrated analysis of space cameras[J]. Optics and Precision Engineering, 2001, 9(4):377-381.
- [6] LI D D, HU M Y, WU H Y, et al. The design of compensation mechanism at low temperature of -213°C[J]. Infrared Technology, 2016, 38(8):659-665.

[7] GUAN H R. Research on structure design of low temperature off-axis reflective collimation system[D]. Hefei: University of Science and Technology of China, 2021.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.